Tapered-Hybrid Bend, Interior-Ridge Modulator and Filter Supporting Tbps-Scale Links

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Abstract: We demonstrate a novel interior-ridge modulator and filter based off a tapered-hybrid bend capable of Tbps-scale DWDM links, enabled by an FSR=37.5 nm, IL_{off}=0.025 dB, and 1.3 nm/mW filter thermal tuning efficiency.

1. Introduction & Background

The explosion in data center traffic and high performance computing highlights the need for energy-efficient and high-bandwidth optical interconnects. Silicon micro-resonators integrated on 300 mm silicon-on-insulator (SOI) wafers are a promising solution, suitable for dense wavelength division multiplexing (DWDM) architectures as shown in Fig. 1a and leveraging existing CMOS facilities for high volume manufacturing (HVM) [1]. However, two of the most common micro-resonator types have trade-offs that can limit aggregate bandwidth and/or cause excessive power consumption. Ring resonators' free spectral range (FSR) are generally limited by excessive radiative losses at small bend radii due to the low optical confinement of the exterior-ridge waveguide needed for electrical contacts [2]. Disk resonators have wide FSRs but relatively high off-resonance insertion loss (IL_{off}) and need additional designs to suppress higher order resonances [3]. When considering HVM, high thermal tuning efficiency is needed to compensate for changes in environmental temperature and re-align channels to target wavelengths due to fabrication-induced variations in resonance location.

Tapered-hybrid bends (THBs) minimize bend losses by using a hybrid-Euler bend with a wider center waveguide width to reduce mode-mismatch, radiative, and scattering losses [4]. Combining two 180° THBs into a racetrack-style resonator and minimizing the effective radius produce a wide FSR without supporting higher order resonances and gives a straight waveguide coupler that lowers the maximum acceptable cumulative IL_{off} (IL_{limit}) compared to a phase-matched coupler [5]. Also, better confinement of the optical mode makes the resonator less sensitive to small changes in waveguide geometry and results in lower variation in fabricated resonance location [6].

Here, we propose and experimentally demonstrate using a THB geometry to create an interior-ridge modulator and complementing filter with a wide 37.5 nm (4.65 THz) FSR, low 0.025 dB (IL_{off}), high 1.3 nm/mW (6.2 µW/GHz) filter thermal tuning efficiency, and an open eye diagram at 32 Gbps — suitable for supporting Tbps-scale links. The internal ridge doubles as RF contacts for the modulator and an efficient heater for the filter. Resonance variation, and by extension thermal tuning power, is reduced by ~45% compared to an equivalent-FSR radial-ridge modulator. This device demonstrates a new combination of attributes that support high-bandwidth and scalable DWDM systems needed for future bandwidth-dense links.

$$N_\lambda = \text{floor}\left[\min\left(\frac{FSR}{\Delta\lambda_{aggressor}}, \frac{IL_{limit}}{IL_{off}} + 1\right)\right]. \tag{1}$$

2. Device Design for Tbps-Scale Links

Aggregate bandwidth is the number of wavelength channels multiplied by the data rate. Prior work described Eq.1, giving the maximum receiver channel count on a bus (N_λ) determined by device parameters of FSR and IL_{off} and link parameters of minimum channel spacing ($\Delta\lambda_{aggressor}$) and IL_{limit}, as illustrated in Fig. 1b [5]. Targeting Tbps-scale links, the first ratio in Eq.1 is maximized by choosing the minimum acceptable $\Delta\lambda_{aggressor}$ for inter-channel crosstalk penalties given the filter's minimum acceptable full-width half-max (FWHM) for the data rate (previously suggested as $\geq 2\times$ data rate). The second ratio is maximized by the lower IL_{off} enabled by the THB geometry. Using an IL_{limit} of 1 dB, measured IL_{off} of 0.025 dB, FSR of 37.5 nm (4.65 THz), data rate of 32 Gbps, and corresponding $\Delta\lambda_{aggressor}$ of 114 GHz (≈0.913 nm) yields a 1.3 Tbps link. For comparison, using a disk filter

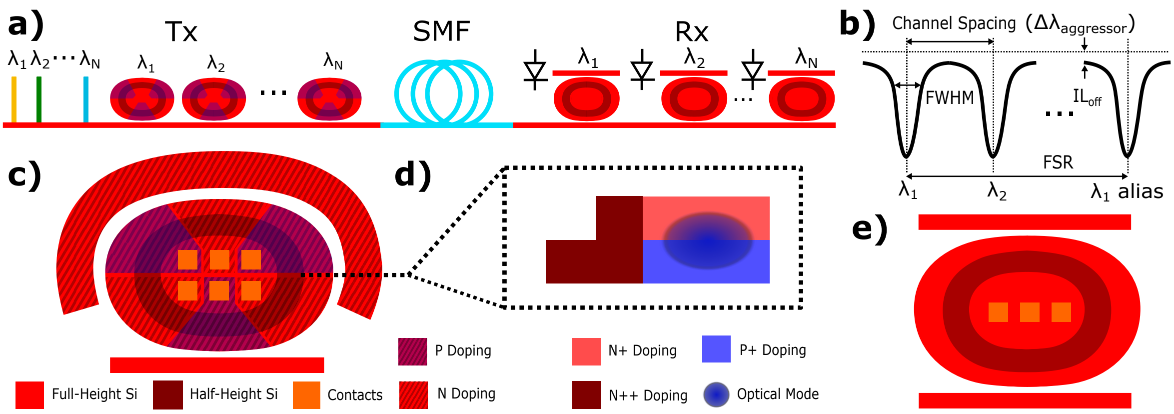

Fig. 1. (a) A DWDM link schematic using THB-ridge modulators and filters. (b) Illustrated N_λ filter parameters described by Eq.1. (c) THB internal-ridge modulator with external heater, racetrack-style, and alternating PN-doped contact scheme. (d) Vertical junction connected by interior full-to-half height N++ doping to ridge, with N++ doping not affecting optical mode. (e) Equivalent THB-ridge filter with internal heater and drop waveguide bus.

with a phase-matched coupler has a higher IL_{off} of $\sim$0.1 dB and results in tolerating an IL_{limit} of 4 dB to match the same aggregate data rate, degrading the signal quality as it cascades through the bus.

For high-speed modulation, shown in Fig. 1c, d, the resistance was reduced by maximizing number of parallel contacts, which was constrained by the foundry's design rule check (DRC) minimum contact spacing and targeted minimum bend radius [7]. Resistance was also lowered by making a full height contact along the inner edge, rather than narrow full height contacts found in a hybrid junction. The modulation efficiency was maximized by using a vertical junction, rather than an interleaved or lateral junction [2]. For thermal tuning, Fig. 1c shows the modulator using an external heater to maximize FSR and Fig. 1e shows the filter heater replacing the center modulation region. This allows a drop bus to a photodiode for signal detection and an increased thermal tuning efficiency from the Si ridge acting as a thermal bridge, since the thermal conductivity of Si is $\sim$100× greater than that of SiO2.

3. Characterization & Modulation

The THB-ridge resonators were fabricated on a 300 mm SOI wafer using AIM Photonics and measured using a ficonTEC WLT-1200 wafer prober. For the THB-ridge modulator, we measured a deep ER of 30.5 dB, FSR of 37.5 nm (4.65 THz), Q of $\sim$6000, depletion response of 45 pm/V (5.7 GHz/V), and thermal tuning efficiency of 0.25 nm/mW (32.6 GHz/V) using a conservative design, with 0.6 nm/mW shown for more optimized designs [8]. The THB-ridge filter had the same target FSR and ER but with a wider designed FWHM of 0.44 nm (55 GHz) and higher thermal tuning efficiency of 1.3 nm/mW (6.2 µW/GHz) as shown in Fig. 2d, f.

As shown in Fig. 2e, there is a 45% reduction in spread of post-fabrication resonance locations across a 64 reticle wafer compared to an equivalent-FSR radial-ridge modulator. This results in a similar power saving if all resonances are tuned to the worse-case resonance location, assuming all devices target some designed absolute wavelength. This sensitivity of fabrication variations is larger in ring designs due to the n_{eff} of the mode being more sensitive to slight changes in the inner and outer sidewalls, whereas the THB and disk have higher mode confinement and only one sidewall, respectively [6]

Fig. 2a, b, c shows the experimental modulation and characterization setup, along with the test structure, and open eye diagram for the THB-ridge modulator. Fig. 2d, e, f shows the spectrum characterization, relative resonance variation, and thermal tuning efficiency for the THB-ridge filter. To demonstrate high-speed operation, a Keysight 81606A tunable laser source (TLS) sent 1540.1 nm light via SMF through a polarization controller (PC) and grating couplers onto a PIC for modulation. The optical output was sent through an Amonics AEDFA-IL-23-B-FA erbium doped fiber amplifier (EDFA) and Thorlabs EVOA1550A variable optical attenuator (VOA) to a Keysight N1092C sampling scope. The RF signal was generated by an Anritsu MP1900A Pulse Pattern Generator (PPG) using a non-return-to-zero (NRZ) pseudo-random bit sequence with bit length $2^{20}-1$ (PRBS20) at 1.3 V_{pp}. This was connected to a Picosecond Pulse Labs bias tee with an applied reverse bias of 1.3 V DC using an external Keithley 2280S DC power supply and the PPG clock was directly fed to the sampling oscilloscope. Fig. 2c shows a clear open eye at 32 Gbps with an OMA of 442 µW and dynamic extinction ratio of 4.2 dB.

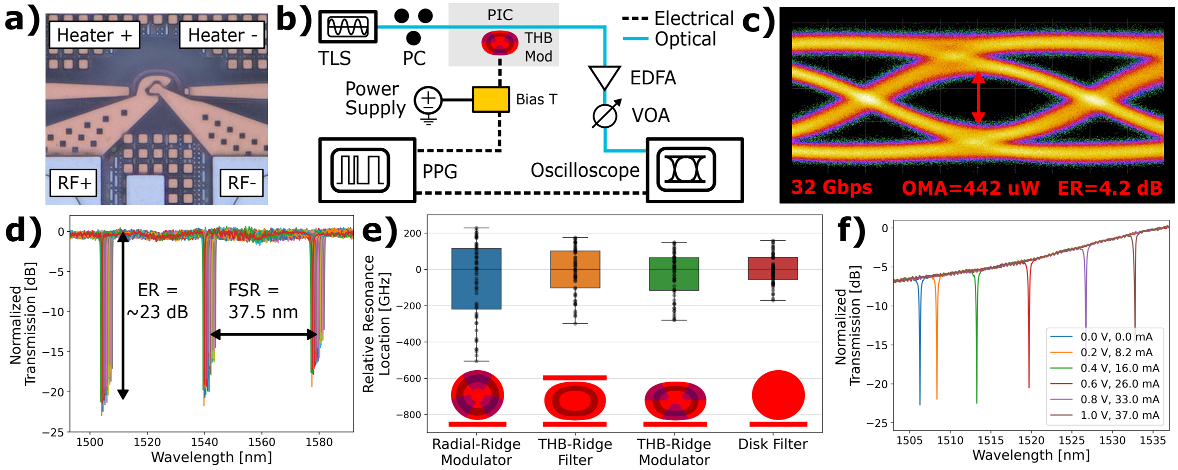

Fig. 2. (a) Micrograph of THB-ridge modulator test structure. (b) Schematic of experimental modulation setup. (c) Eye diagram at 32 Gbps driven at 1.3 V_{pp}, dynamic ER = 4.2 dB, and OMA = 442 µW. (d) Wafer-scale plot of THB-ridge filter spectra. (e) Boxplot of relative resonant wavelength spread across different devices. (f) Thermal tuning plot of THB-ridge filter.

4. Conclusion

Using a THB geometry to create an interior-ridge modulator and complementary filter uniquely combines the best attributes of ring and disk modulators, namely high FSR, low IL_{off}, single-mode operation, and insensitivity of target resonant wavelength location to fabrication variations. These newly proposed and demonstrated THB-ridge resonator designs offer a way towards meeting the high bandwidth demands for future scalable and energy-efficient Tbps-scale links.

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